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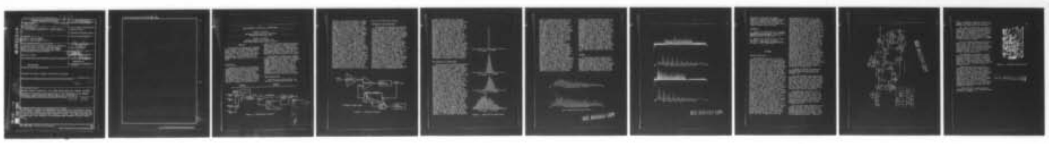

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Symposium Paper

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ABSTRACT

The Stochastic Syncoder was developed as an element of an experimental communication system. However, its design was based on observed neuron activity, and in itself is able to simulate the firing of a neuron. This paper describes the hardware model, and considers its performance when compared to actual neural data.

INTRODUCTION

Modeling the firing of an individual neuron has been going on for many years. These models include mathematical models, computer simulations, and electronic hardware realizations. Of the latter group, the circuits themselves tend to be deterministic, that is, they are made of fixed components. Stochastic effects are simulated by adding noise to the input signal. This paper discusses a new circuit, designated a "Stochastic Syncoder." This circuit realized stochastic effects by utilizing a random element in the circuit itself. An internal noise source is used to vary a threshold parameter in a random manner. The magnitude and average level of the noise can be adjusted, allowing the statistical distribution of the output pulses to be varied.

The Stochastic Syncoder was developed as an element of an experimental communication system, rather than for the express purpose of modeling a neuron. However, neural behavior was the basis for the design. The resulting circuit can be tuned to provide a response which is quite comparable to that of a primary auditory neuron, both for no stimulus (spontaneous firing) and for sinusoidal stimuli. It is this ability of the Stochastic Syncoder to simulate neural activity that is presented in this paper.

BASIC NEURON MODEL

The action of a single neuron can basically be described as follows. The

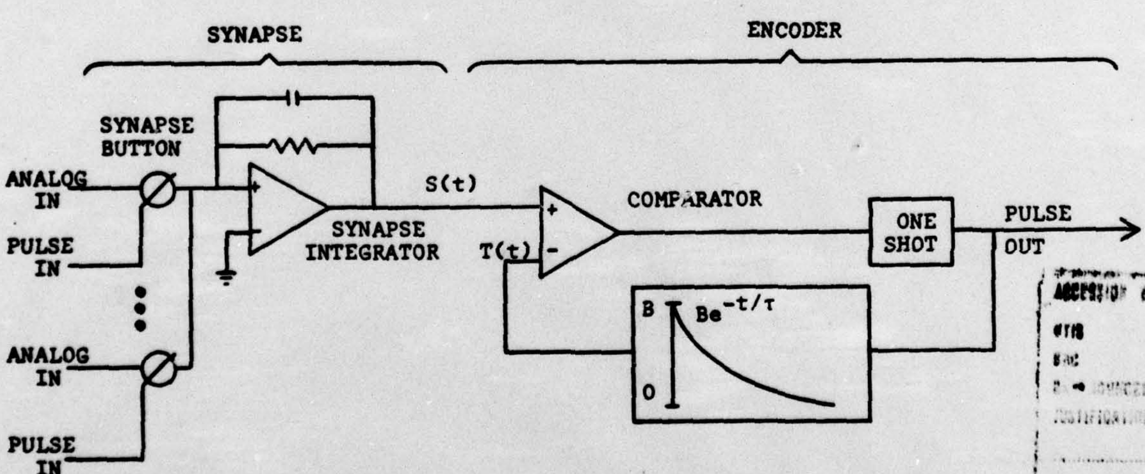


Figure 1. Deterministic Syncoder

"input" to the neuron consists of connection from axons of other neurons to dendrites of the neuron in question. These connections are called synapses. The signals arriving from other neurons are temporally and spatially summed to form a post-synaptic potential. This potential is compared to an internal threshold. When the post-synaptic potential exceeds this threshold the neuron fires. Immediately after firing, the neuron is inhibited from firing for a finite period known as the absolute refractory period. These features are all contained in the model shown in Figure 1. The diagram divides the model into a <u>syn</u>apse and an en<u>coder</u>, from which the name Syncoder is derived.[1] The deterministic Syncoder shown in Figure 1 models the basic neural action described above. The input signals are temporally and spatially summed by the synapse integrator to form the post-synaptic potential S(t). This is compared to the exponentially decaying threshold T(t) during the relative refractory period by the comparator. When S(t) exceeds T(t) the comparator triggers the one-shot, producing an output pulse. The one-shot also holds the threshold at its peak value B for the duration of the pulse, thus simulating the absolute refractory period. The deterministic model of Figure 1 was realized as an electrical circuit and formed the starting point for the development of the Stochastic Syncoder.

STOCHASTIC MODEL DEVELOPMENT

The Stochastic Syncoder was developed as an element of an experimental statistical communication system. Since the concept for this system was based on the observation of auditory eighth nerve data of guinea pigs, it was desired to simulate the stochastic properties of these primary auditory neurons as closely as possible. For its intended function a synaptic summation wasn't needed, so in the Stochastic Syncoder the synapse circuit was reduced to a unity gain buffer amplifier. Looking at the remaining encoder portion of Figure 1, it was decided to inject the random behavior into the threshold generator. Four techniques for adding randomness were investigated. The first approach was to add noise directly to the threshold function T(t). This approach is equivalent to adding noise to the input S(t), an approach taken by other investigators.[2] The second approach was to make the reset value of the threshold, B, a random variable. Thus at the beginning of each relative refractory period k the threshold would decay from an initial value B(k), statistically different from the previous starting point B(k-1). The remaining two approaches utilized the threshold decay rate τ

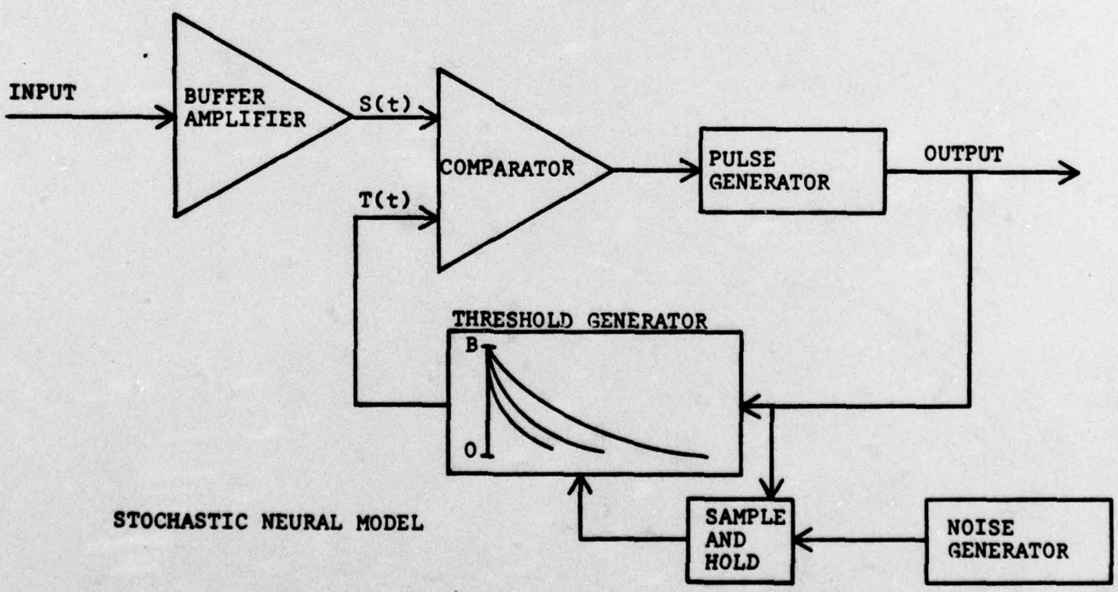


Figure 2. Stochastic Syncoder

as the random variable. In the third approach τ was continuously variable, τ(t). Thus the decay rate was continuously changing during the decay interval. The resulting threshold function did not look like a smooth exponential decay, but rather like a wiggly line varying around an exponential mean. In the final approach the decay rate was a discrete variable. At the beginning of the relative refractory period k, a random value was selected for τ(k). This value remained constant during the decay, so that a smooth exponential curve could be observed, and was reset to a new value τ(k+1) at the beginning of the next sample. Breadboard models were built of all four techniques, and the output pulses sampled and analyzed by the same computer system used to analyze the eighth nerve response. Based on their ability to simulate the neural data as well as consideration of their ultimate application, the fourth approach, the discretely random decay rate, was selected for prototyping. This model is shown in Figure 2. A description of the circuit used to realize this model is presented in the Appendix.

THE CIRCUIT AS A NEURON MODEL

The system used to measure performance of the electronic circuit is basically identical to that used to record actual single neuron response. A gated stimulus signal is generated, along with a corresponding synchronizing pulse. A variety of signals are possible, but only sine waves have been used for these tests. The stimulus is presented to the input of the circuit, and the output pulses are sampled by a PDP-11 computer. The software can generate several displays, but the Pulse Interval Histogram (PIH) is the most useful. In the PIH the abscissa represents the interval lengths between any two successive pulses, and the ordinate indicates the number of times a given interval occurred during the run. (A run consists of 100 presentations of the stimulus). The primary tuning of the circuit parameters is accomplished using a spontaneous firing, which is induced by a slight DC input to intercept the exponential decay of the threshold. With the amplitude of the noise generator set to zero, the model degenerates to a deterministic Syncoder, with output pulses occurring at equal intervals. This is indicated by a single vertical line at that interval value of the PIH, as shown in Figure 3(a). By changing the DC bias voltage on the noise amplifier, this line can be positioned anywhere on the PIH within the range of allowable time constants. A slight increase in the noise amplitude to 1.7 millivolts (mV) RMS pro-

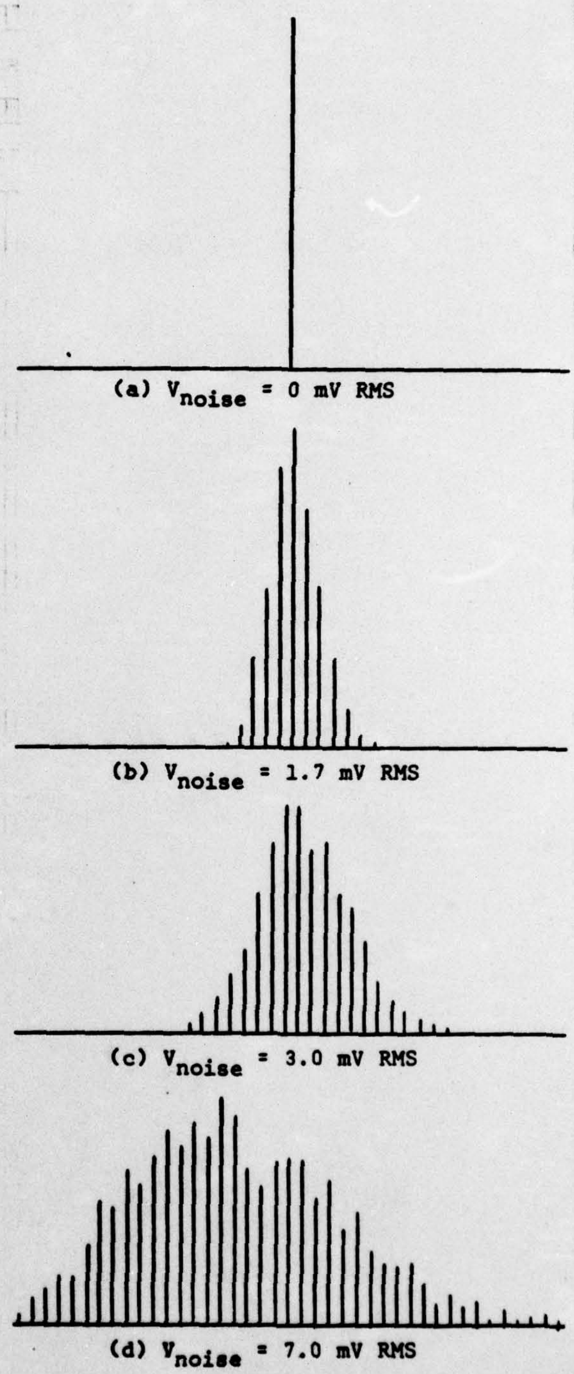
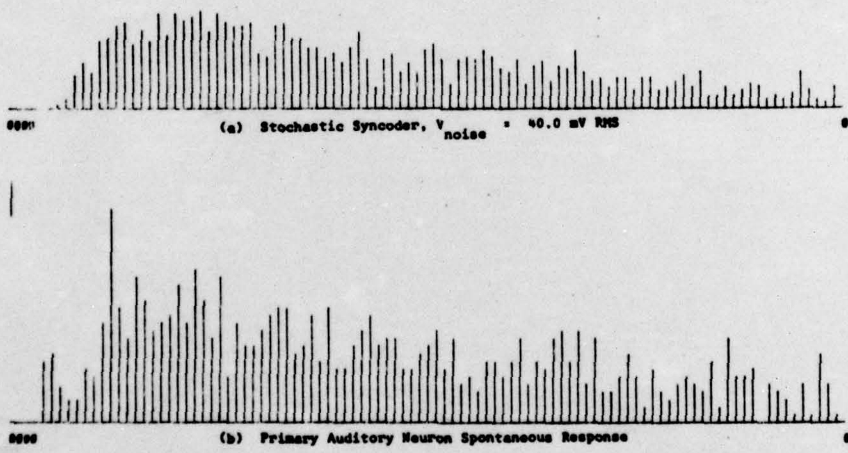


Figure 3. Output PIH For Small Noise

duces the symmetrical distribution of output intervals shown in Figure 3(b). Now a change in the DC bias voltage will shift the entire distribution to the right or left. Further small increases in noise continue to broaden the distribution, as in Figure 3(c), but before long the distribution begins to take on a distinct skew to the left, as shown in Figure 3(d) for a noise voltage of 7.0 mV RMS. Finally, by increasing the noise voltage to 40.0 mV RMS, and shifting the mode to the left with the DC bias, a distribution comparable to the spontaneous firing of a primary auditory neuron is achieved, as shown in Figure 4. Further comparison of the model with actual neural data was accomplished by comparing their response to sinusoidal stimuli. This class of stimuli was chosen based on available neural data and on the absence of the synaptic integrator in the model, which would probably be required for more complex stimuli. A single stimulus consists of a time delay following the sync pulse, then a sinusoidal signal gated on for 200 milliseconds. This was repeated every 500 milliseconds for a total of 100 stimuli. A typical response for the model is shown in Figure 5 for a 555 Hz sine wave. The upper histogram is the Pulse Occurrance Histogram (POH), which represents the number of times a pulse occurred (ordinate) at a particular time (abscissa) after the sync pulse (origin). The gated sinusoid stands out clearly as the series of tall spikes, and the remaining low activity represents spontaneous activity. The lower plot is the PIH and shows peaks occurring at subharmonics of the sinewave. The corresponding results for a primary auditory neuron are shown in Figure 6. Note that a longer delay after sync was used in the stimulus for the model. Based on visual comparison of such data from both the Stochastic Syncoder and primary auditory neurons, it appears that the Stochastic Syncoder represents a fairly good model for the firing of a primary neuron, at least in response to sinusoidal stimuli and for spontaneous activity. The next logical step would be to add the synapse integrator (which could easily be achieved by the addition of a feedback capacitor to the imput buffer amplifier) and continue these tests for various other stimuli.

SUMMARY

In this paper a basic deterministic model of the firing of a single neuron has been defined and four tentative ways of adding random activity indicated. Based on preliminary testing of breadboard models, the technique which uses a fixed decay rate whose value randomly changes from one decay interval to the next was found to be most representative of neural activity. An electronic circuit was



(a) Stochastic Syncoder, V_{noise} = 40.0 mV RMS

(b) Primary Auditory Neuron Spontaneous Response

Figure 4. Spontaneous Response of Syncoder and Neuron.

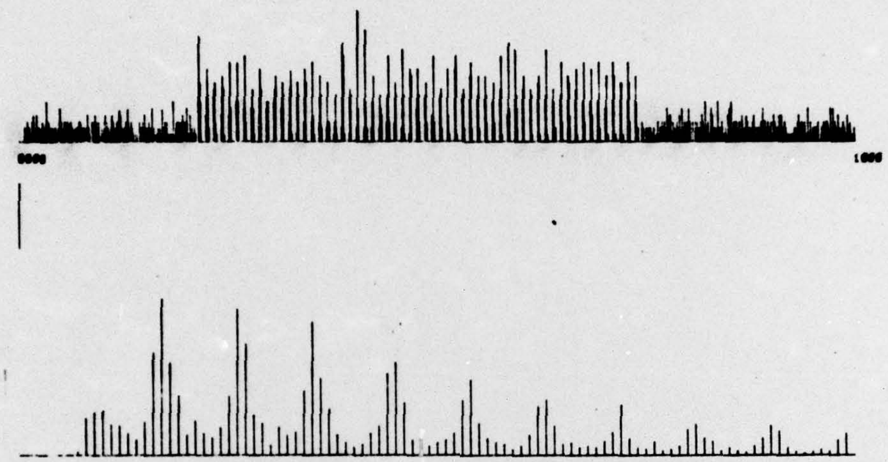


Figure 5. Response of Stochastic Syncoder to 555 Hz Stimulus.

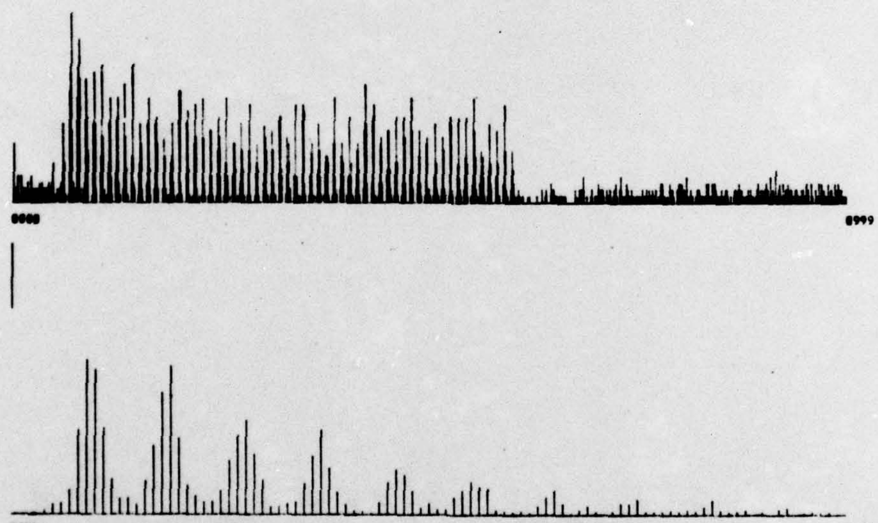


Figure 6. Response of Primary Auditory Neuron to 555 Hz Stimulus.

developed to implement this model. Finally, output pulse histograms from the model were compared with similar histograms from primary auditory neurons of a guinea pig to show that the model could indeed simulate neural activity.

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APPENDIX

CIRCUIT DESCRIPTION

The Stochastic Syncoder is realized from the model of Figure 2 using the circuit shown in Figure 7. The encoding operation of the Stochastic Syncoder is based upon the comparison of an input signal to an internally generated random exponential decaying threshold voltage. When the input signal and threshold voltage are equal, a pulse output is generated. At this time the threshold decay voltage is reset and the time constant is changed in the threshold decay circuit. The input signal S(t) and bias voltage are summed through an inverting operational amplifier A-1. The output is wired to the noninverting input of a high speed voltage comparator, A-2. The inverting input of the comparator is wired to the threshold decay voltage circuit. When the two inputs are equal, an output pulse occurs. This pulse is used for two functions. First, the pulse passes through a level converter and triggers a timer, A-7. This timer generates an output pulse with a width varying from 10 μsec to 1 msec determined by potentiometer R2. The second function of the comparator pulse is to switch the FET switch A-5b ON to allow the threshold decay circuit to begin to recharge. This pulse is ORed with the output pulse from A-7 so that the FET will remain ON during the output pulse duration. After that duration, the FET switch A-5b is turned OFF and the RC circuit begins to discharge. The output pulse from the timer, A-7, also turns ON FET switch A-5a. This switch causes the track-and-hold circuit to begin tracking the voltage from the diode noise generator. After the output pulse duration is complete, the circuit holds the last voltage value from the noise generation circuit, A-4. The track-and-hold circuit is an FET operational amplifier. It is necessary to utilize its high input impedance to prevent droop during the output pulse interval. A-4 is connected to the gate of the MPF-108 field effect transistor. The key component in the generation of the random decay time constant is a FET, used as a voltage variable resistor in the threshold decay network. To randomly set the effective resistance and thus the threshold time constant, a random voltage must be generated. This voltage is generated by sampling the output of the noise generator during the output pulse interval, then holding that voltage for the duration of the decay period, until the next output pulse is generated. The random noise generator consists of a 12 volt zener diode operated in the avalanche breakdown mode. The diode is coupled into a FET differential operational amplifier circuit with a gain of one hundred. The output of the amplifier is connected through potentiometer R3 to another amplifier circuit. The second amplifier circuit is used to set both the noise amplitude level (R3) and the DC bias level (R4). These two parameters control the operation of the FET used in the decay threshold circuit, and allow one to set the mode and variance in the resulting Pulse Interval Histogram, as described in the main text.

A number of special considerations were necessary when this circuit was designed. These considerations are listed below.

A-3, the threshold decay operational amplifier has to have a FET input. This input has a characteristic high impedance and very low bias currents which yields very good linearity and low circuit loading. There is an 89 pF capacitor across pins 1 and 8 to prevent spurious oscillation. There is also a potentiometer, R1, that improves circuit linearity and helps prevent circuit instability.

The operational amplifier, A-3, in the threshold decay circuit is set to have a gain factor of ten. This is required because of the MPF-108 FET. The 3.92 KΩ and 392 KΩ precision resistors form a 1.2 volt source. Therefore, when the threshold decay circuit is fully charged it will never exceed the FET voltage limitation.

Pin 8 of the op-amp comparator A-2 has a diode attached. The purpose of the diode is to limit the output pulse to a voltage swing of 0 to +12 volts. This improves the speed of the circuit. The 220 pF capacitor and 47 KΩ resistor form a pulse generation network. This net-

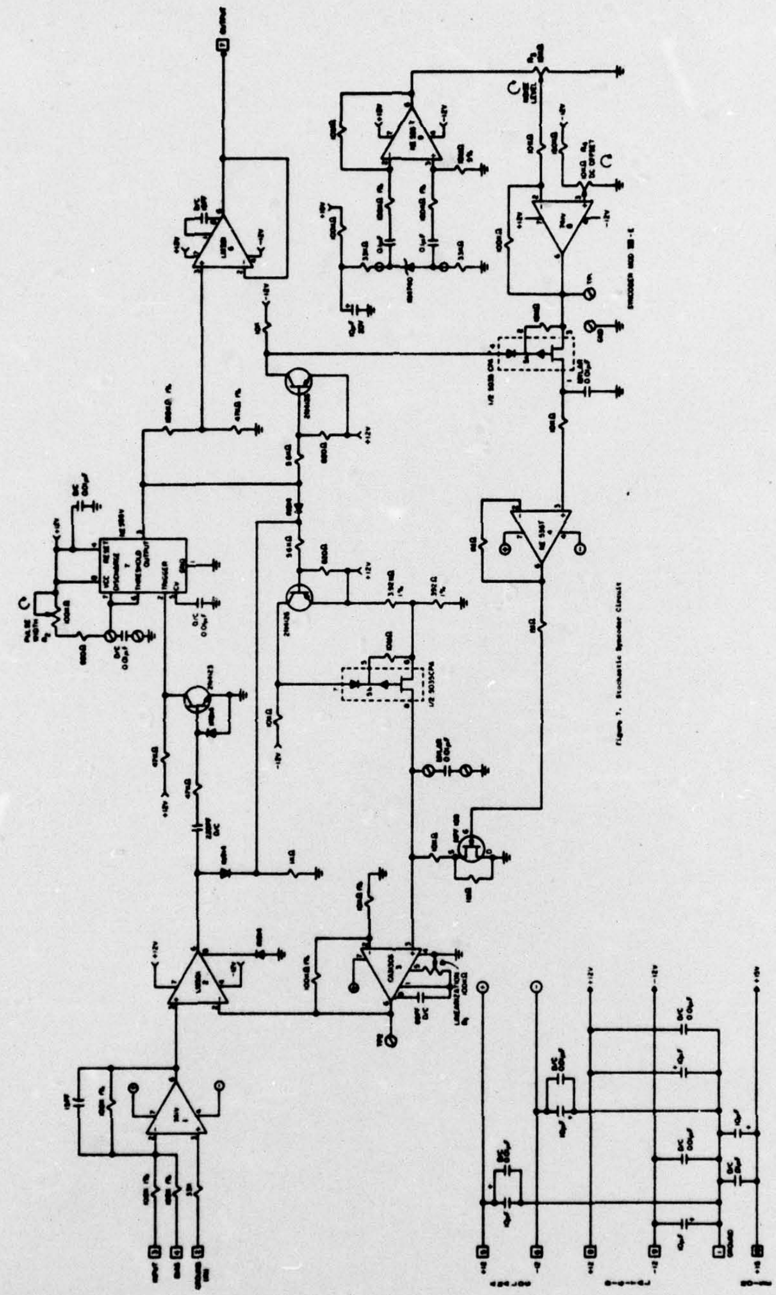

Figure 7. Stochastic Speaker Circuit

work is necessary to generate a pulse to trigger the NE555V timer, A-7, and it also prevents any possible circuit latch-up.

The output pulsewidth of the timer A-7 can be varied with the pulsewidth potentiometer R2. The range of pulsewidths can be changed by replacing the .01 μF capacitor connected between pin 7 and ground of A-7. The output of the timer also is connected to a precision resistor voltage divider network. This network is designed to act as a level shifter.

A-6 is an output op-amp circuit with a gain of one. The output level from A-6 will change from 0 to 3.5 volts. This output level will allow the encoded signal to be demodulated with either an analog or digital decoder. A 15 pF capacitor is connected across pins 1 and 8 of A-8 to prevent spurious oscillation.

The IH5035CPA is designed to operate into the noninverting input of an operational amplifier. The gate of each FET has been brought out so that a "referral resistor" can be placed between the gate and source. This resistor value is 10 meg ohms and is used to minimize charge injection effects.

Separate power supplies were provided for the analog and digital portion of the Syncoder circuits. This was an attempt to prevent the current spiking in the digital logic supplies from affecting the operation of the sensitive analog circuits. There was also a separate power supply provided for the noise generator circuit. This prevented any noise from being interjected into unwanted portions of the circuit. This also prevented any unwanted cross talk from being coupled and amplified through the noise generation circuits.

A printed circuit board was fabricated for the model, and a completed board is shown in Figure 8.

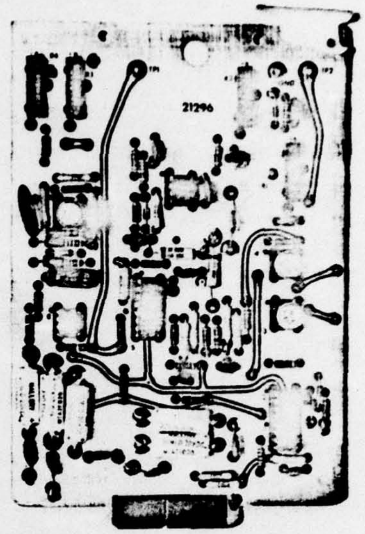

Figure 8. Stochastic Syncoder Board